Mighty Small Dots

. . . nanoscience and nanotechnology will change the nature of almost every human-made object in the next century.

—The Interagency Working Group on Nanotechnology, January 1999

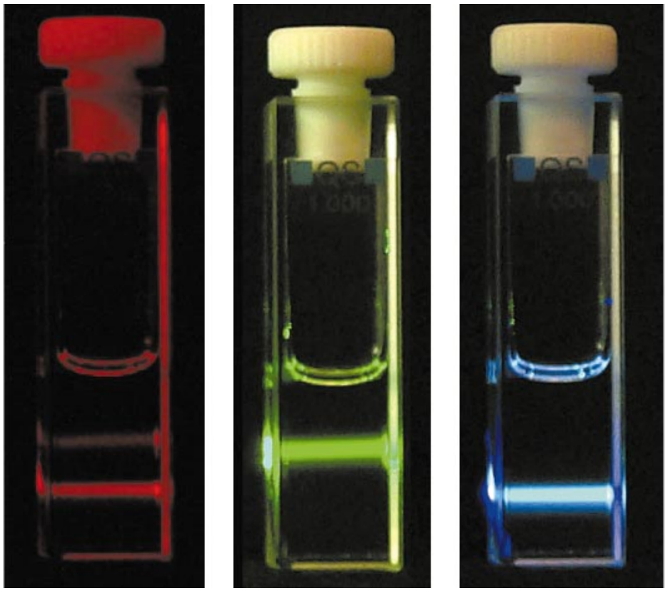
SMALLER . . . smaller . . . smaller. In the semiconductor industry, this mantra translates to faster . . . faster . . . faster. The question is, how small can you go?

At Lawrence Livermore National Laboratory, the answer may be: as small as quantum dots. Physicist Howard Lee and his team of Laboratory and University of California at Davis researchers have been exploring these entities, which are about a single nanometer (a billionth of a meter) in size and made out of material such as silicon. Lee explains, "Imagine taking a wafer of silicon and cutting it in half again and again and again, until you have a piece containing about a hundred to a thousand atoms. That's the size we're looking at."

The small size results in new quantum phenomena that yield some extraordinary bonuses. Material properties change dramatically because quantum effects arise from the confinement of electrons and "holes" in the material (a hole is the absence of an electron; the hole behaves as though it were a positively charged particle). Size changes other material properties such as the electrical and nonlinear optical properties of a material, making them very different from those of the material's bulk form. If a dot is excited, the smaller the dot, the higher the energy and intensity of its emitted light. Hence, these very small, semiconducting quantum dots are gateways to an enormous array of possible applications and new technologies.

"For years," says Lee, "scientists have been trying to make silicon emit light efficiently and in the visible range. This has been one of the holy grails of science." In 1990, researchers from Europe made porous silicon emit red light and attributed its color to quantum confinement arising from the small size. Since then, many other research institutions and commercial companies have taken an interest in quantum dots and have made silicon dots that emit at frequencies higher in the spectrum, in the much-sought-after green and blue ranges. In general, these higher energy emissions tend to be difficult to reproduce and not well understood.

"Here at the Laboratory," says Lee, "we have made silicon and germanium quantum dots that emit light throughout the visible spectrum—from the infrared to the ultraviolet. What makes our dots unique is that their luminescence can be tuned to any wavelength over a broad spectral range and be stable under ambient conditions. No one else has done this. We also believe we understand the underlying physics."



Howard Lee and his colleagues have synthesized silicon and germanium quantum dots ranging in size from 1 to 6 nanometers. The larger dots emit in the red end of the spectrum; the smallest dots emit blue or ultraviolet.

Smaller Is Beautiful

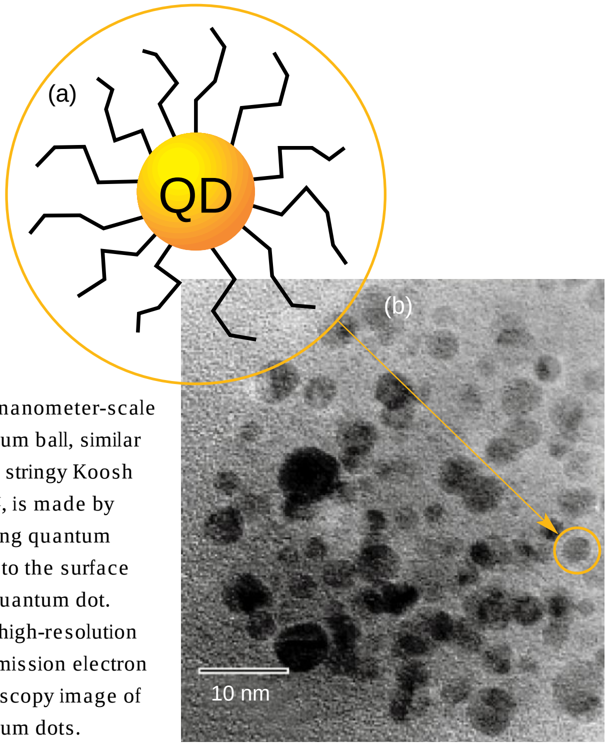
The color of the emitted light depends on the size of the dots: the larger the dot, the redder the light. As the dots shrink in size, the emitted light becomes shorter in wavelength, moving toward the blue. A rainbow of colors can be emitted from a single material simply by changing the dot size.

One possible use for this rainbow of colors is in biosensors used to detect agents of biological warfare. "Present-day fluorescence-based biosensors depend on organic dyes to tag the agents. The dyes luminesce to tell you whether any harmful bioagent is present," says Lee. "The problem is, dyes luminesce with a broad spectral width, which limits their effectiveness to a small number of colors. Furthermore, they degrade. Using quantum dots instead of dyes, the whole spectrum is available and there is little degradation over time."

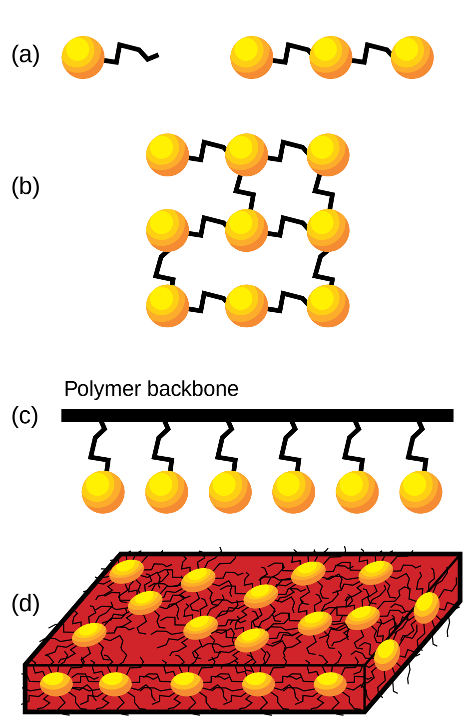
"With all these different colors, it's now possible to make light-emitting diodes (LEDs) from quantum dots," says Lee. "We've come up with a process so easy you can almost do it in your garage. We can put these dots in a polymer and make thin films that are 1,000- to 2,000-angstroms thick. This means we can create precisely tuned blue or green LEDs."

Another future use for quantum-dot LEDs is to emit white light for uses in laptop computers or as internal lighting for buildings or cars. Lee and his team have discovered they can—by controlling the amount of blue in the emission—control the "flavor" or "tone" of the white light as well.

Quantum dots are also possible materials for making ultrafast, all-optical switches and logic gates. "We can make all-optical switches and logic gates that work faster than 15 terabits a second," says Lee. For comparison, the Ethernet



(a) A nanometer-scale quantum ball, similar to the stringy Koosh Ball™, is made by bonding quantum wires to the surface of a quantum dot. (b) A high-resolution transmission electron microscopy image of quantum dots.



With molecular tethers to link them together, quantum dots become the building blocks of nanostructures. They can be linked together as (a) molecules, (b) lattices, (c) attached to a polymer backbone, or (d) incorporated into a polymer thin film.

generally can handle only 10 megabits per second. Quantum dots provide a remarkable millionfold improvement in speed. Other possible applications are all-optical demultiplexers (for separating various multiplexed signals in an optical fiber), all-optical computing, and encryption.

The frantic pace of innovation in semiconductors requires that integrated circuits be made with ever smaller features to carry more data and do it faster (see *S&TR*, March 1998, pp. 24–26, and November 1999, pp. 4–9). Most semiconductor fabrication processes start with a silicon wafer and etch away unneeded wafer material. Quantum dots, Lee explains, allow a bottom-up approach: “If you only need 100 atoms, then that’s what you make. And a single quantum dot can function as a microelectronic unit such as a transistor to form the basis of nanoelectronics.” At sizes of 1 to 6 nanometers, billions of dots will fit on the head of a pin. They will have incredibly fast operating speeds—1 picosecond or less—and extremely low power requirements.

Connecting the Dots

In a current Laboratory Directed Research and Development project, Lee is developing quantum wires to connect the dots together in a variety of configurations. As Lee notes, “If you use regular or even microscopic connections to link these dots, the size of the connections could destroy any useful quantum effects and defeat the purpose.”

The quantum wires are molecular tethers made of organic compounds chemically bonded to the surface of the dot. They can be of various lengths—the longest created to date is about 12 angstroms long—and serve multiple functions. They can be electrically or optically active molecular structures. The wires on the dots add up to a nanometer-scale version of the popular kids’ toy, the stringy Koosh Ball™.

Using these wires and dots, Lee and his team are developing new nanostructures with quantum dots as the building blocks. The team is linking the dots in various one-, two- or three-dimensional configurations—as a molecule, a lattice, or attached to a polymer backbone. The molecular tethers act like electrical wires to the dots or as a way to control the interaction of connected dots.

Into the Wild, Blue Yonder

Quantum-dot LEDs, particularly those that provide the hard-to-reach blue end of the spectrum, appear to be key to opening any number of exciting technological advances in the fields of full-color, flat-panel displays; ultrahigh-density optical memories and data storage; backlighting; and chemical and biological sensing. “We have also explored the use of quantum dots for blue lasers,” notes Lee. “In 1999, we demonstrated that lasing may be possible with these quantum dots, opening the door to a new class of blue lasers that have intriguing applications for both the private sector and the missions of the Department of Energy.”

—Ann Parker

Key Words: all-optical switch, demultiplexer, light-emitting diode (LED), logic gate, quantum dot, quantum effects, semiconductor.

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